

Neutrino Spin Flavor Precession and Leptogenesis

Juan Barranco,¹ Roberto Cota,¹ David Delepine,¹ and Shaaban Khalil^{2,3}

¹*Division de Ciencias e Ingenierías, Universidad de Guanajuato,
Campus Leon, C.P. 37150, León, Guanajuato, México.*

²*Centre for Theoretical Physics, Zewail City of Science and Technology, Sheikh Zayed, 12588, Giza, Egypt.*

³*Department of Mathematics, Faculty of Science, Ain Shams University, Cairo, Egypt.*

(Dated: March 3, 2013)

We argue that $\Delta L = 2$ neutrino spin flavor precession, induced by the primordial magnetic fields, could have a significant impact on the leptogenesis process that accounts for the baryon asymmetry of the universe. Although the extra galactic magnetic fields is extremely weak at present time (about 10^{-9} Gauss), the primordial magnetic field at the electroweak scale could be quite strong (of order 10^{17} Gauss). Therefore, at this scale, the effects of the spin flavor precession are not negligible. We show that the lepton asymmetry may be reduced by 50% due to the spin flavor precession. In addition, the leptogenesis will have different feature from the standard scenario of leptogenesis, where the lepton asymmetry continues to oscillate even after the electroweak phase transition.

PACS numbers: 12.60.Cn, 12.60.Cr, 13.15.+g

I. INTRODUCTION

Observations indicate with high level of accuracy that the present universe contains no significant amount of baryonic antimatter [1, 2]. Thus, the baryonic matter we are made off is the remanent of a small matter-antimatter asymmetry originated at the early universe. This asymmetry can not be explained within both the Standard Model of Particle Physics (SM) and the Standard Model of Cosmology, usually called Lambda Cold Dark Matter (Λ CDM). Fortunately, an elegant explanation of the observed baryon asymmetry is offered by neutrino physics. This mechanism requires right-handed Majorana neutrinos that decay out-of-equilibrium. This decay process, combined with non-perturbative anomalous electro-weak processes, can generate the baryon number in the universe [3–7]. In this ‘leptogenesis’ generation of the baryon asymmetry, it is expected that the lepton asymmetry to be of the same order of magnitude that of the baryon asymmetry, due to sphaleron effects that are relevant for temperature from 10^{12} GeV to 100 GeV [8, 9]. The measurement of the Baryon Asymmetry of the Universe (BAU) through the anisotropies of the cosmic microwave background radiation (CMB) together with other cosmological observations at a very high level of precision have strongly constrained BAU, that is parameterized by the ratio of baryon number to photon number: $\eta_B = N_B/N_\gamma$. Recent analysis [10] implies that

$$\eta_B = (5.8 \pm 0.27) \times 10^{-10}, \quad (1)$$

which show that the measurement of baryon asymmetry is achieved with an error less than 5%.

In addition, the neutrino physics is also reaching high precision measurements. Recently the last lepton mixing matrix angle θ_{13} has been measured [11]. These progresses should permit to test leptogenesis models. So it is very important to have a reliable way to describe the production of the lepton asymmetry taking into account all $\Delta L \neq 0$ processes. In fact, the lepton asymmetry is not

precisely measured as the baryon asymmetry. Recently, it has been trying to constraint the lepton asymmetry from WMAP and nucleosynthesis [12]. The following limits on $\eta_L = (N_{\nu_L} - N_{\bar{\nu}_L})/N_\gamma$ have been obtained:

$$-0.071 < \eta_L < 0.054. \quad (2)$$

It is clear that these limits are far from the accurate precision of the baryon asymmetry. Nevertheless, new WMAP measurements and better knowledge on neutrino mixing matrices would permit to improve these results.

The fact that non diagonal neutrino magnetic moment μ_ν could induce a neutrino-antineutrino transition due to a helicity flip produced by the interaction of μ_ν with an external magnetic field is known since a long time. It has been called Spin-Flavor precession (SFP) effect. This effect was originally used to explain the solar neutrinos deficit [13–15, 17]. However, after the confirmation of mixing mass explanation by KamLAND [18], the SFP is used as a mechanism to constraint μ_ν [19]. In this letter, we consider the implications of the neutrino SFP on $\Delta L = 2$ processes and leptogenesis. To our knowledge, this is the first time that this neutrino-antineutrino transition is analyzed in the context of $\Delta L = 2$ process that might affect the leptonic asymmetry produced in early universe. The effect of a primordial magnetic field on baryogenesis have already been studied [25, 25–27] but it has been done using the standard model anomaly terms which violates $B + L$ quantum numbers and not through SFP process.

The letter is organized as follows. In section II we briefly review the neutrino spin flavor precession, induced by the primordial magnetic fields. In section III the time dependent magnetic fields at early universe is discussed. Section IV is devoted for a possible lepton asymmetry generated by the SFP process. In section V the associated leptogenesis induced by SFP is studied. Finally our conclusions and remarks are given in section VI.

II. NEUTRINO SPIN FLAVOR PRECESSION

The assumption that neutrino magnetic moment could be an explanation to the deficiency of the solar neutrino flux through Spin Precession effect were exposed by Cisneros more than 40 years ago [13] and generalized later to the case of Majorana neutrinos [28]. It is well known that left-handed fermion with magnetic moment could be affected by the Spin Precession effect (SP) which induces in presence of magnetic field a transition from left to right handed fermions or inversely [16]. For the Majorana neutrinos the diagonal components of magnetic moments vanish and the off-diagonal components are related by $-\mu_{e\mu} = \mu_{\mu e} \equiv \mu_\nu$ leading to processes violating flavors and lepton number. In order to find the probability of the $\nu_{eL} \rightarrow \nu_{\mu L}^c$ transition, we need to study the evolution of the chiral components of two flavors of neutrinos, which is described by a Schrödinger type equation [29]. In general, in a medium with arbitrary matter density and magnetic field profiles, no analytical closed-form expression for the transition probability can be obtained. In this case one has to solve Schrödinger equation numerically, which is quite straightforward. Since we are interested at early epochs of the universe ($T \sim 10^{11}$ GeV), we ignore the neutrino masses and the electron-neutron energy densities. Hence, the solution to the Schrödinger type equation [29] with an arbitrary magnetic field is given by

$$P(\nu_{eL} \rightarrow \nu_{\mu L}^c; t) = \sin^2 \left(\int_{t_0}^t \mu_\nu B_\perp(t') dt' \right). \quad (3)$$

where $B_\perp(t)$ is the transverse magnetic field strength, t being the time appearing in the Schrödinger equation. This formula is valid for an arbitrary magnetic field profile $B_\perp(t)$. It is interesting to note that Eq. (3) is valid after the electroweak breaking scale in a first approximation due to the fact that the energy of the neutrino E is given by the temperature T which is much bigger than Δm^2 , so the terms proportional to $\Delta m^2/E$ can still be neglected. It is important to notice that the SFP will not stop at Electroweak breaking scale but will continue up to our days. This can be understood from Eq. (3), where the probability depends on the magnitude of the magnetic moment and time scale. It is clear that at every times *i.e.*, t is very small, the magnetic field B must be extremely large in order to imply a large SFP effect. While at late time *i.e.*, t is very large, a reasonable SFP effect can be obtained with smaller values of B . As an example let us consider a constant magnetic field of order 10^4 G, it is clear that the SFP effect is irrelevant between the scale of right-handed neutrino decays ($t_{M_1 \simeq 10^{11} \text{ GeV}} \simeq 10^{-30} \text{ s}$) and electroweak symmetry breaking ($t_{EPT} \simeq 10^{-11} \text{ s}$). However, its effect becomes important at time around the big bang nucleosynthesis (BBN).

It is remarkable that the spin flavor precession probability violates the lepton number by two units ($\Delta L = 2$).

Therefore, we can conjecture that such term may affect the Leptogenesis scenario.

III. TIME-DEPENDENT MAGNETIC FIELDS AT EARLY UNIVERSE

The main constraints on SFP processes are coming from limits on primordial magnetic field at photon decoupling time obtained through observing microwave background radiation [30] which puts a limit on present time magnetic field to be smaller than 3×10^{-9} G [20]. This limit should be translated into the primordial time assuming that the magnetic field evolution is given by

$$B(t) \simeq B(t_i) \left(\frac{a(t_i)}{a(t)} \right)^2, \quad (4)$$

where $a(t)$ is the scale factor, assuming Friedman Robertson Walker dynamics for the Universe. Usually, the relation between the magnetic fields at different cosmological time is not so simple but for simplicity, we shall assume this scaling factor (for detailed discussion see ref. [24]). This means that the CMB limit on present value of the primordial magnetic field could be roughly translated into a limit of order $10^9 G$ for the primordial magnetic field at BBN time [21, 24], which correspond to a time of around 100 s after Big Bang¹. Thus, it is crucial to translate this bound on the primordial magnetic fields at electroweak symmetry breaking scale and up to the scale of right-handed majorana neutrino decoupling (M_1 around 10^{11} GeV), where the leptogenesis process takes place. At these times (which correspond to radiation domination era), the scale factor is given by

$$a(t) \propto t^{1/2}. \quad (5)$$

Thus, the bound on magnetic field at electroweak scale is of order 10^{17} G and at M_1 scale is around $10^{27} G$. In this respect, we assume that our time-dependent magnetic field between the time associated to the scale of the heavy right-handed Majorana Neutrinos typically given by $M_1 \simeq 10^{11} \text{ GeV}$ and the time (t_{EPT}), which corresponds to the time when the Electroweak Phase Transition (EPT) occurs, is given by:

$$B(t) \simeq B(t_{EPT}) \frac{t_{EPT}}{t} \quad (6)$$

where $B(t_{EPT}) \simeq 10^{17} G$.

¹ In Ref. [22], it has been claimed that the limits on gravitational waves could bound much stronger than the BBN bounds. But in more recent studies [23], it has been shown that the limits on cosmological magnetic fields set by the latest LIGO S5 data lie close to those obtained by BBN and the CMB. For a review on Primordial Magnetic fields see ref. [24]

IV. SPIN FLAVOR PRECESSION AND LEPTON ASYMMETRY

We now study the effect of spin-precession process on light, mainly left-handed, majorana neutrino assuming the existence of a time-dependent primordial magnetic fields given in Eq.(6). In order to include in the Boltzman equation the terms corresponding to the spin-precession effects, it is important to recall in two flavor case that the variation $\Delta N_{\nu_{1,2}}$ in $\nu_{1,2}$ number density due to SFP is given by

$$\Delta N_{\nu_1} = P(\nu_2^c \rightarrow \nu_1) N_{\nu_2^c} - P(\nu_1 \rightarrow \nu_2^c) N_{\nu_1} \quad (7)$$

$$\Delta N_{\nu_2} = P(\nu_1 \rightarrow \nu_2^c) N_{\nu_1} - P(\nu_2^c \rightarrow \nu_1) N_{\nu_2^c} \quad (8)$$

where the first term in Eq. (7) account for the number of ν_2^c 's which have been changed into ν_1 and the second term is equal to the number of ν_1 's which have been changed into ν_2^c . Similar equations can be built for $\Delta N_{\nu_{1,2}^c}$. Defining the lepton number density as

$$N_L \equiv N_{\nu_1} + N_{\nu_2} - N_{\nu_1^c} - N_{\nu_2^c},$$

and assuming CP is conserved (*i.e.*, $P(\nu_1 \rightarrow \nu_2^c) = P(\nu_1^c \rightarrow \nu_2)$), one gets

$$\Delta N_L = -2PN_L \quad (9)$$

where P is the probability of SFP given by Eq. (3). This approach can be easily extend to n_f flavors and we obtain

$$\frac{dN_L}{dt} = -2(n_f - 1) \frac{d}{dt} (PN_L). \quad (10)$$

This equation represents a new contribution for the lepton asymmetry that will affect the leptogenesis scenario. Thus, the lepton number density $N(t)$ is given by

$$N_L(t) = \frac{N_L^0}{1 + 2(n_f - 1)P(\bar{\nu} \rightarrow \nu)}, \quad (11)$$

where N_L^0 is the initial lepton number density. It is clear that for probability $P(\bar{\nu} \rightarrow \nu) \simeq \mathcal{O}(1)$, the lepton asymmetry can be reducing respect to its initial value by a factor $1/5$.

It is worth mentioning that for magnetic fields below $10^{14} G$ and due to limit on the neutrino magnetic moment [19] to be $\mu < 10^{-12} \mu_B$, where μ_B is the Bohr magneton, one can easily check from Eq.(3) that the SFP process is irrelevant between the scale of right-handed neutrino decays (t_{M_1}) and electroweak symmetry breaking time (t_{EPT}). So for primordial magnetic field smaller than $10^{14} G$, SFP process will not affect directly the usual leptogenesis scenario. However as it will be shown explicitly below, it will continue to affect the lepton asymmetry even after the electroweak symmetry breaking, transforming it as a time-oscillating function. This is important as in usual leptogenesis scenario, the lepton and baryon asymmetry of the Universe are related through a simple relation which only depends on matter contents of the model. Even with a relatively weak primordial magnetic field (below $10^{14} G$), this relation between η_L and η_B is lost.

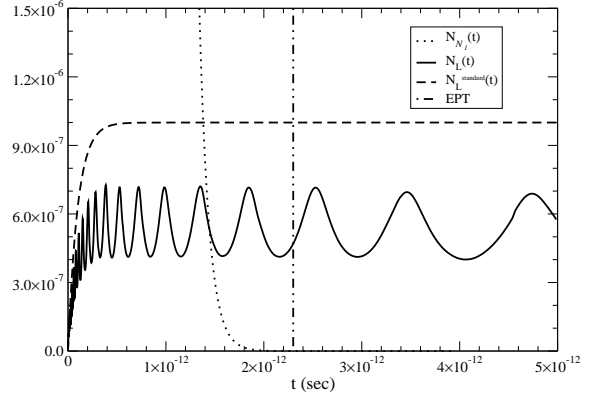


FIG. 1: The continue oscillating line corresponds to η_L including SFP effects. The dash line is η_L as expected from standard leptogenesis scenario. The vertical dotted-dash line represents an approximate value for Electroweak Phase Transition Time (t_{EPT}). For $t > t_{EPT}$, the η_L is not anymore converted into η_B through $B + L$ violating sphalerons. The dotted line show the evolution of the heavy RH majorana neutrino density N_1

V. LEPTOGENESIS AND SPIN FLAVOR PRECESSION

Here, we assume a strong primordial time-dependent magnetic field, given by Eq.(6), before electroweak phase transition and compatible with present limits on cosmological magnetic fields. In order to get the SFP effects on Leptogenesis standard scenario², we solve the Boltzman equation of the heavy right-handed (RH) majorana neutrino, N_1 , that decays violating CP and producing a lepton asymmetry through usual leptogenesis scenario. This lepton asymmetry is transformed into the Baryon Asymmetry of the Universe through anomalous $B + L$ violating sphaleron processes which are in equilibrium between $10^{12} GeV > T > 100 GeV$. For simplicity and in order to clearly see the SFP effects on Boltzman equations, we assume that the $\Delta L = 1$ scattering processes in Boltzman equation for heavy RH majorana neutrinos are out of equilibrium and that the only relevant terms is the one describing the heavy RH neutrino decays and inverse decays. Also, for the N_L Boltzman equation, we assume that all $\Delta L \neq 0$ processes induced by heavy neutrinos are out of equilibrium and are not able to wash out any produced lepton asymmetry. Within these approximation, the basic equations for leptogenesis including SFP effects are given by

$$\begin{aligned} \frac{dN_{N_1}}{dt} &= -\Gamma_D N_1 \\ \frac{dN_L}{dt} &= \epsilon \Gamma_D N_{N_1} - 2(n_F - 1) \frac{d(PN_L)}{dt} \end{aligned} \quad (12)$$

² for a detail description of Leptogenesis standard scenario see for instance ref. [7]

where Γ_D represent the Direct and Inverse Decay and N_1 is the heavy RH Majorana neutrino density. From [7], we use $\epsilon = 10^{-6}$ and Γ_D is given by

$$\Gamma_D = \frac{1}{8\pi} \frac{m_1 M_1}{v^2} M_1 \frac{K_1(z)}{K_2(z)}. \quad (13)$$

where $K_i(z)$ are the Bessel functions, and m_1 is the effective light neutrino mass, v is the usual electroweak symmetry breaking scale and M_1 is the heavy RH neutrino mass[7]. The results of integrating these equations are shown in Fig 1. The EPT corresponds to an approximate evaluation of the Electroweak Phase transition time which corresponds to the moment when the BAU is frozen but as one can see from fig 1, the lepton asymmetry continue to oscillate. It is also important to notice that the total lepton asymmetry produced during leptogenesis is reduced compared to Standard scenario. This means that if we want to use leptogenesis scenario and BAU measured value to constraint neutrino masses, the effects of the magnetic fields should be taken into account as it reduced the lepton asymmetry by 50%. Also the uncertainties on t_{EPT} implies that in presence of strong primordial magnetic fields, the uncertainties on the produced BAU could be as large as 50% due to oscillating behavior of the lepton asymmetry.

VI. CONCLUSION

We have studied the impact of the neutrino spin flavor precession, induced by primordial magnetic fields, on

the lepton asymmetry and leptogenesis process. We have shown that contrary to what could be naively expected from the weakness of the extra and intra galactic magnetic fields at present time, primordial magnetic fields in Early Universe could be large enough to significantly affect Leptogenesis scenario. With such strong magnetic field at electroweak symmetry breaking time, we have shown that the SFP effects reduce the lepton asymmetry by around a factor 50% and increase the uncertainties on the produced BAU as the uncertainties on the electroweak phase transition time which corresponds to the freezing of the BAU are important. Even for magnetic fields too weak to modify Leptogenesis scenario, their presence induces an oscillating behavior for the lepton asymmetry at later stage in the History of the Universe, leading to lose the relation between Lepton and Baryon asymmetry as usually given in Leptogenesis models. A profile for the magnetic fields up to time around 100 seconds after Big Bang is needed in order to perform more precise numerical.

Acknowledgements

The work of S. K. is partially supported by the ICTP grant AC-80. D.D. is grateful to Conacyt (México), DAIP project (Guanajuato University) and PIFI (Secretaria de Educacion Publica, México) for financial support.

-
- [1] G. Steigman. *Ann.Rev.Astron.Astrophys.*, 14:339–372, 1976.
 - [2] Gary Steigman. *JCAP*, 0810:001, 2008.
 - [3] M. Fukugita and T. Yanagida. *Phys.Lett.*, B174:45, 1986.
 - [4] M.A. Luty. *Phys.Rev.*, D45:455–465, 1992.
 - [5] Esteban Roulet, Laura Covi, and Francesco Vissani. *Phys.Lett.*, B424:101–105, 1998.
 - [6] W. Buchmuller and M. Plumacher. *Phys.Lett.*, B431:354–362, 1998.
 - [7] W. Buchmuller, P. Di Bari, and M. Plumacher. *Annals Phys.*, 315:305–351, 2005.
 - [8] V.A. Kuzmin, V.A. Rubakov, and M.E. Shaposhnikov. *Phys.Lett.*, B155:36, 1985.
 - [9] V.A. Matveev, V.A. Rubakov, A.N. Tavkhelidze, and M.E. Shaposhnikov. *Sov.Phys.Usp.*, 31:916–939, 1988.
 - [10] Gary Steigman. arXiv:1008.4765 [astro-ph.CO].
 - [11] J. K. Ahn *et al.* [RENO Collaboration], arXiv:1204.0626 [hep-ex].
 - [12] Emanuele Castorina, Urbano Franca, Massimiliano Lattanzi, Julien Lesgourgues, Gianpiero Mangano, et al. 2012. 10 pages, 7 figures, 5 tables.
 - [13] Arturo Cisneros. *Astrophys.Space Sci.*, 10:87–92, 1971.
 - [14] L.B. Okun, M.B. Voloshin, and M.I. Vysotsky. *Sov.J.Nucl.Phys.*, 44:440, 1986.
 - [15] L.B. Okun, M.B. Voloshin, and M.I. Vysotsky. *Sov.Phys.JETP*, 64:446–452, 1986.
 - [16] E. K. Akhmedov, hep-ph/9705451.
 - [17] O.G. Miranda, Carlos Pena-Garay, T.I. Rashba, V.B. Semikoz, and J.W.F. Valle. *Nucl.Phys.*, B595:360–380, 2001.
 - [18] J. Barranco, O.G. Miranda, T.I. Rashba, V.B. Semikoz, and J.W.F. Valle. *Phys.Rev.*, D66:093009, 2002. new appendix added discussing the impact of the KamLAND data. This updates the one published in Phys.Rev.D66:093009,2002.
 - [19] O.G. Miranda, T.I. Rashba, A.I. Rez, and J.W.F. Valle. *Phys.Rev.Lett.*, 93:051304, 2004.
 - [20] Dario Grasso and Hector R. Rubinstein. *Phys.Rept.*, 348:163–266, 2001.
 - [21] J.J. Matese and R.F. O’Connell. *Phys.Rev.*, 180:1289–1292, 1969.
 - [22] Chiara Caprini and Ruth Durrer. *Phys.Rev.*, D65:023517, 2001.
 - [23] Shuang Wang. *Phys.Rev.*, D81:023002, 2010.
 - [24] Alejandra Kandus, Kerstin E. Kunze, and Christos G. Tsagas. *Phys.Rept.*, 505:1–58, 2011.
 - [25] Massimo Giovannini and M.E. Shaposhnikov. Primordial hypermagnetic fields and triangle anomaly. *Phys.Rev.*, D57:2186–2206, 1998.
 - [26] V.B. Semikoz and J.W.F. Valle. Lepton asymmetries and

- the growth of cosmological seed magnetic fields. *JHEP*, 0803:067, 2008.
- [27] V.B. Semikoz, D.D. Sokoloff, and J.W.F. Valle. *Phys.Rev.*, D80:083510, 2009.
- [28] J. Schechter and J.W.F. Valle. Majorana Neutrinos and Magnetic Fields. *Phys.Rev.*, D24:1883–1889, 1981.
- [29] Chong-Sa Lim and William J. Marciano. *Phys.Rev.*, D37:1368–1373, 1988.
- [30] Kiyotomo Ichiki, Keitaro Takahashi, and Naoshi Sugiyama. *Phys.Rev.*, D85:043009, 2012.